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What Is a Sustainable Level of Timber Consumption in the EU: Toward Global and EU Benchmarks for Sustainable Forest Use

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Abstract: Renewable energy targets in the European Union (EU) have raised the demand for timber and are expected to increase dependence on imports. However, EU timber consumption levels are already disproportionally high compared to the rest of the world. The question is, how much timber is available for the EU to sustainably harvest and import, in particular considering sustainable forest management practices, a safe operating space for land-system change, and the global distribution of "common good" resources. This article approaches this question from a supply angle to develop a reference value range for the current as well as future sustainable supply of timber at the EU-27 and global levels. For current supply estimates, national-level data on forest area available for wood supply, productivity in that area, as well as the rate available for harvest were collected and aggregated into three potential supply scenarios. For future supply estimates, a safe operating space scenario halting land use change, a sensitivity analysis, and a literature review were performed. To provide both a comparison of global versus EU sustainable supply capacities and to develop a benchmark toward evaluating and comparing levels of consumption to sustainable supply capacities, per capita calculations were made. Results revealed that the per capita sustainable supply potential of EU forests is estimated to be around three times higher than the global average in 2050. Whether a global or EU reference value is more appropriate for EU policy orientation, considering both strengthened economic and cultural ties to the forest in forest-rich countries as well as the need to prevent problem shifting associated with exporting land demands abroad, is discussed. Further research is needed to strengthen and harmonize data, improve methods for modeling future scenarios and incorporate interdisciplinary and multi-stakeholder perspectives toward the development of robust and politically relevant reference values for sustainable consumption levels.

Keywords: monitoring; global land use; safe operating space; sustainable consumption and production; targets; resource management

1. Introduction

EU citizens consume more timber annually than global citizens on average and their consumption levels are expected to rise significantly over the next decades [1–3]. Meeting renewable energy targets with wood will significantly increase EU timber demand. If the EU Renewable Energy Directive targets of 2009 were to be realized, one study calculated that wood consumption for energy generation would have to more than double between 2010 and 2030 (from around 346 million cubic meters (Mm^3) to 752 Mm^3), considering optimistic assumptions regarding efficiency gains and an increased share of other renewables [4]. Meeting this increased demand through an increased harvest of forests within the EU seems unlikely [2]. According to [1], "even if all measures for increased wood mobilization [in the EU] are implemented, wood industry demand and renewable energy targets can hardly be satisfied from domestic sources in 2020" [1] (p. 22). This implies an increased dependence on imports and raises concerns as to how and where imported timber shall be sourced [5].

The key question is thus: how much timber is available for the EU to harvest and import considering sustainability constraints? In this context, sustainability constraints relate in particular to:

- the sustainable use of existing forests (how are forests managed and how much timber can be sustainably extracted under those management conditions?)
- global land use change, specifically the safe operating space for land-system change (how much timber will be available if deforestation continues and how much land is available for expanding the area of plantations?)
- global distribution of "common good" resources considering equity and fairness (how much should the EU consume and is the concept of "fair shares" appropriate for timber?).

With regards to the first consideration, the concept of sustainable forest management (SFM) has evolved substantially over the last few decades. It has gone from viewing SFM through the lens of sustainable timber supply only to widely recognizing that sustainability includes social, ecological, and economic considerations across time, and that forests provide multiple services in each of these areas that are worthy of maintaining [6–9]. What this means for timber production capacities in quantifiable terms at a global scale is yet undefined. It does, however, imply that a massive shift toward monoculture plantations or that mobilization of large-scale removal of residues and stumps to source wood for energy may not be in keeping with sustainability considerations on the ground.

The importance of halting global land use change has emerged as one of the key sustainable development challenges of this century. In particular, it is one of the nine planetary boundaries [10,11], where it is argued that the conservation of global forest cover (e.g., at least of 54–75% of original forest cover [12]) is critical to existing climate systems, as well as global biodiversity. With regards to future timber consumption, this implies that possible land constraints for the expansion of plantations exist, especially in tropical regions where maintaining forest area and quality is especially crucial for preserving biodiversity.

Within the EU the need to pursue sustainable levels of consumption that respect resource constraints and planetary boundaries has been recognized by the European Commission [13]. In particular, in light of growing timber imports, the aim for sustainability seems to be finding a balance between how much can be sustainably extracted globally and how much the EU has a "right" to consume considering equity and fairness.

To this end, this article takes a first step toward developing a method to account for sustainable timber supply capacities and to assess the applicability of results as benchmarks for sustainable consumption levels of timber. In the future, such "benchmark indicators" (or reference values) could be further developed to provide a direct comparison and basis for evaluating the sustainability of e.g., timber "footprints". The aim is to move beyond comparisons of national supply and demand levels to develop a way to (a) include global pressures related to imports and (b) provide a future orientation for informing policies consistent with the aims of, e.g., the Sustainable Development Goals. As such, this article develops initial concepts and methodological building blocks, presents rather indicative results, and discusses in detail the challenges related to data, methods, as well as research with the aim of initiating a conversation about the need for such "benchmark indicators" as part of an EU-wide systemic monitoring system for the sustainable use of natural resources.

Specifically, this article develops a reference value range for the current supply as well as future supply taking into account land use constraints. Reference value ranges at both EU and global scales are estimated in per capita terms and the appropriateness and applicability of both for benchmarking the sustainability of EU consumption are discussed. The article concludes with a discussion of challenges and future research needs, including the socio-ethical implications for reference values with the perspective of development towards targets.

2. Materials and Methods

Both global and EU reference value ranges were developed for (1) current levels of sustainable supply and (2) future levels of sustainable supply; they were (3) transferred into per capita values.

2.1. Determining a Reference Value Range for the Current Levels of Supply

To estimate the amount of available timber under sustainable conditions, a range of national level data was gathered, estimated, and aggregated to depict EU and world forests. This was done in three steps by estimating for each country the:

- Forest area available for wood supply (hectares (ha))
- Productivity of that area (cubic meters per hectare and year (m^3 ha^{-1} a^{-1}))
- Rate at which that forest can be expected to sustainably supply timber (sustainable harvest level) (m^3 a^{-1}).

Due to data variation as well as considerable data gaps, a range for each of the steps was calculated to develop low, realistic, and high potential estimates. Table 1 describes the key definitions and data sources for the first two steps. The realistic potential estimates distinguished natural and semi-natural forests from fast-growing plantations. "Fast-growing" was defined by this study to mean a Mean Annual Increment (MAI) above 14 m^3 ha^{-1} a^{-1} or a rotation length under 20 years. In this way, some of the trends associated with changing forest structures could be captured.

Table 1. Definitions and data source for potential estimates of FAWS and NAI.

Forest Area Available for Wood Supply (FAWS)		Productivity: Net Annual Increment (NAI)	
Definition	**Key Sources**	**Definition**	**Key Sources**
Forest where any legal, economic (e.g., accessibility), or specific environmental restrictions do not have a significant impact on the supply of wood	[14,15]	The average annual volume over the given reference period of gross increment less that of natural losses on all trees to a minimum diameter at breast height of 0 cm	[14]
Forest theoretically available for wood supply, which comprises all forest area minus forest in protected areas [1]	[16]	Highest potential estimate of NAI	
Forest realistically available for wood supply, which comprises the best estimate based on literature sources and available data	National sources [2] and [14–17,20–23]	Best potential estimate of NAI. 'Fast-growing plantations' estimated based on MAI and 'natural/semi-natural forest area' on NAI	[14,15,17–20]
Minimum forest available for wood supply, which comprises a modest estimate based on literature sources and available data	Lowest minimum estimate from above sources (in case >2 estimates available) or 25% less than the realistic estimate [3]	Lowest potential NAI estimate	

Notes: [1] "Allowing" harvest on all of these lands is not likely to meet sustainability criteria and would probably be unrealistic and unfeasible. First, this includes a large forest resource that is undisturbed by man. This area includes areas of high nature value (where protection and conservation seem critical) and is inaccessible (no roads). Second, this vast forest resource is an important carbon sink and keeping the forest intact is key to the climate agenda. The high potential is thus indicative of a theoretical availability for comparative purposes, but is neither likely nor desirable; [2] Use of national sources was limited due to issues of e.g., data comparability. For a full list see the Annex of [24]. Three values were selected based on best judgment for depicting a range of results; [3] Value selected based on best judgment for depicting a range of results.

For countries with no data available, judgment was used to estimate country conditions based on, e.g., regional averages. Data on NAI is much more developed for countries with temperate and boreal forests than for countries with tropical forests. For countries with data on NAI available, this data was taken as the realistic potential, and a range was estimated using other available sources or Gross Annual Increment (GAI) as the high estimate. According to [20], the MAI of well-managed tropical forests is around 1 m^3 ha^{-1} a^{-1}. This estimate was generally used as a baseline for the low estimate of tropical countries. For countries with no data, especially the "Global fibre supply model", [17] was used as a basis for estimates. It reports GAI for all countries, which was used as the high potential range, with the realistic potential range assumed to be 25% and the low potential range 50% less than the continent average.

The harvest rate under sustainable management conditions is location-specific. It also depends on, for example, the management objectives, type of forest, age of the forest, and silviculture practices. Ideally, the sustainable harvest rate on the forest available for wood supply would be collected from local sources, which have defined sustainable forest management objectives that are locally-appropriate and culturally acceptable, and aggregated to a global level. However, this information is not yet available.

As a basic principle, to maintain an intact forest resource at a landscape level, less timber should be removed than grows annually. As the EU has a target to halt biodiversity loss by 2020 in the EU and to step up the EU contribution to averting global biodiversity loss [25], it seems reasonable and transparent to use as a basic rule "harvesting below NAI" as a maximum threshold. However, to keep other ecosystem services provided by forests in mind, this threshold may be too high. It has been argued that a 60–70% appropriation of total global wood biomass increment (including protected and inaccessible areas) required to meet 20% of current global primary energy consumption—will erode current biomass pools, lower average stand age, and deplete soil fertility [5]. Moreover it would shift forest structures toward shorter rotations, simplifying canopy structure and composition with impacts on ecosystem diversity, function, and habitat. This implies that sustainable harvest rates should be below 100% of NAI. More research is urgently needed to determine what this rate for different types of forests is. Until better data is available, this article has calculated three indicative potentials for a "sustainable" harvest rate: 80% of NAI; 90% of NAI; 100% of NAI.

To determine the global threshold for the sustainable supply of primary timber, the forest area available for wood supply (ha) and the productivity of that area (m^3 ha^{-1} a^{-1}) were multiplied to determine the volume which could be harvested annually (m^3 a^{-1}) under different rates of potential sustainability (e.g., harvesting 80%, 90%, and 100% of NAI). The low potential estimate for forest area was multiplied by the low potential estimate for productivity, the realistic potential estimate for area was multiplied by the realistic potential estimate for productivity, and the high potential estimate for area was multiplied by the high potential estimate for productivity. Thus, the calculated potential ranges depict the minimum and maximum possible supply of timber.

2.2. Toward a Reference Value Range for Future Timber Supply

To determine a reference value range for the sustainable production of primary timber in the future, three basic steps were undertaken:

- A "safe operating space" scenario halting land use change was developed
- A sensitivity analysis to check assumptions regarding area, productivity, and management was performed
- A literature review to check the consistency of results was undertaken

2.2.1. Halting Land Use Change

To reflect the need to halt land use change in order to stay within the planetary boundaries, a safe operating space (SOS) scenario until 2050 was developed. The SOS scenario halts all changes in forest area by 2020 for both natural forests and fast-growing plantations. This is based on the assumptions made by [26,27] for halting the expansion of global cropland by 2020. Both studies promoted halting the expansion of cropland into forests, grasslands, and savannahs with the aim of halting the loss of biodiversity associated with land use change (e.g., habitat loss) based on global biodiversity assessments [28,29]. This article follows that same logic, suggesting to halt both deforestation and degradation (in this case a change from, e.g., natural forests to plantations) by 2020 in order to halt the loss of biodiversity connected to land use change. The planetary boundary for biodiversity loss determined by [10–12] is estimated to have already been surpassed, lending credence to this rationale. Moreover, the EU supports the aim to "halt global forest cover loss by 2030 at the latest and to reduce gross tropical deforestation by at least 50% by 2020 compared to current levels" [30] (p. 5). The SOS scenario used here is thus somewhat more ambitious than current goals, but nevertheless aligned with existing council conclusions. It is also more ambitious than the planetary boundary for forest cover change suggested by [12], which is related primarily to the climate impacts of forest cover change rather than the biodiversity impacts.

The implications of the SOS scenario on the forest are manifold. First, land currently used as, e.g., managed forests for timber supply, would continue to be used as managed forests in the future by replanting after harvest. Second, logging the forest to replace it with cropland, pastures, fast-growing plantations or built-up land would be halted beyond 2020. Third, there is also an inherent implication that significant net afforestation would not occur beyond 2020.

To determine the amount of forest area change until 2020, the aggregated average annual change rate of the period from 2000 to 2010 of global forests and EU-27 forests based on FAO data were extrapolated. Aggregated trends were assessed because extrapolation with a bottom-up assessment at the level of countries skewed the results due to significant return of forest growth in some countries during 2000–2010, especially China, which offset global deforestation losses in the scenarios at a rate unlikely to continue in the future.

To determine the potential wood supply available, it was assumed that the same share of forest available for wood supply (FAWS) in the total forest area in 2010 would be available in 2050. This implies that overarching forest trends have the same impact on the FAWS area as they have on the total area. To determine the supply available (volume), the same NAI ranges applied in 2010 were applied to 2050. Realistic potential estimates of FAWS and NAI were used for future scenarios because the range determined by low and high potential estimates was considered too broad for a meaningful interpretation and because, e.g., the high potential represents a theoretical boundary that does not necessarily reflect sustainability conditions (it assumes that all forests not within conservation areas are available for timber supply, but parts of these forests may be inaccessible and include areas of high biodiversity). To determine the sustainable supply, it was assumed that an 80% share of NAI is available in 2050 under sustainable forest management conditions. This was chosen to be consistent with results from the prior section and is an area in urgent need of research.

With regards to fast-growing plantations, the annual average area expansion estimated by [31] in their business-as-usual scenario was extrapolated until 2020. To estimate yearly production volumes, a productivity rate increase of 0.25% per year was assumed to reflect the trend of increasing yields from these types of plantations over time.

2.2.2. Sensitivity Analysis

A sensitivity analysis was performed to test the effect of changing assumptions in the three parameters: forest area, forest productivity, and forest management (with regards to a "sustainable" forest harvest rate). In some cases, these parameters do not correspond with criteria for what could be considered a sustainable use of the forest resource and as such are not necessarily indicative of a SOS sustainable supply scenario. Table 2 depicts the assumptions tested for both the global and EU-27 scenarios. These assumptions differ somewhat based on circumstances. For example, as the EU-27 already has a high share of FAWS, the sensitivity analysis looked at the effect of e.g., decreasing FAWS to 75% in 2050. The 75% was chosen as a theoretical exercise to correspond with a 25% share of forests in protected areas, consistent with one scenario of the EFORWOOD project (which was an EU project with the objective of developing the TosIA tool for sustainability impact assessment for the forest sector. The 25% was a case study for testing the tool [32]). However, it should be recognized that forest not available for wood supply (FnAWS) is not a proxy for protected areas (see also the definitions in Table 1) and this, as with many of the assumptions tested in the sensitivity analysis, represents more of a hypothetical thought-experiment. In some cases, only data based on the EU country analysis was found, in which case EU assumptions were applied to the world. For example, a 4% increase or decrease in productivity per decade is consistent with the expected impacts of climate change on European forests [33]. With regards to the sustainable harvest rate, the sensitivity analysis depicts the changed results (e.g., −12% to +13% at a global scale) from selecting a lower or higher harvest rate, and thus emphasizes the need for further research toward this important parameter. In Table 2, the baseline in both cases depicts the results of timber availability in the SOS scenario in 2050 and the right hand column for both the global and EU-27 scenarios shows the differences to the baseline that the changed assumptions would make. In general, the impact of changed assumptions appears to be larger at the global scale than for the EU-27.

Table 2. Sensitivity analysis assumptions and results.

Global				**EU-27**			
	Results	**Diff. to Baseline**			**Results**	**Diff. to Baseline**	
	Mm^3	**Mm^3**	**%**		**Mm^3**	**Mm^3**	**%**
BASELINE	**3851**	**-**	**-**	**BASELINE**	**656**	**-**	**-**
Area				**Area**			
Forest area trends from the period 1990–2000 extrapolated	3839	−11	0%				
Forest area trends from the period 2005–2010 extrapolated	3848	−3	0%				
No increase in plantation area	3772	−79	−2%	No increase in plantation area	653	−3	0%
Decrease in plantation area by 10% per decade	3543	−308	−8%	Decrease in plantation area by 10% per decade	651	−5	−1%
Decrease in plantation area by 20% per decade	3378	−472	−12%	Decrease in plantation area by 20% per decade	649	−8	−1%
Increase in plantation area by 10% per decade	4081	230	6%	Increase in plantation area by 10% per decade	655	−1	0%
Increase in plantation area by 20% per decade	4487	636	17%	Increase in plantation area by 20% per decade	657	1	0%
Increase FAWS by 2% per decade	4383	533	14%	FAWS increases to 87% of the forest area	672	16	2%
Increase FAWS by 5% by decade	5182	1331	35%	FAWS decreases to 75% of the forest area	583	−73	−11%
Productivity				**Productivity**			
Natural forests: Productivity increases by 4% per decade	4360	509	13%	Natural forests: Productivity increases by 4% per decade	760	104	16%
Natural forests: Productivity declines by 4% per decade	3399	−452	−12%	Natural forests: productivity declines by 4% per decade	564	−92	−14%
Plantations: Productivity increases by 1% per year	4146	296	8%	Plantations: productivity increases by 1% per year	671	15	2%
Plantations: Productivity decreases by 1% per year	3514	−336	−9%	Plantations: Productivity decreases by 1% per year	639	−17	−3%
Forest management				**Forest management**			
Harvest 90% of NAI	4332	481	13%	Harvest 90% of NAI	738	82	13%
Harvest 70% of NAI	3369	−481	−12%	Harvest 70% of NAI	574	−82	−13%
Plantations: Harvest 100%	4063	213	6%	Plantations: harvest 100%	667	11	2%

2.2.3. Literature Review

The results of steps one and two were compared to available estimates of sustainable supply in the literature in order to derive a reference value range consistent with key literature sources. In this sense, the reference value range should reflect the current state of research, in particular for the EU, in which a greater number of studies assessing sustainable supply capacities are available. The literature review was performed by collecting, identifying, and evaluating key studies in the field, including both project reports as well as journal articles.

2.2.4. Deriving a Future Sustainable Supply Range

Steps one (land use change scenario), two (sensitivity analysis), and three (literature review) were combined in a pragmatic approach to derive a global and EU reference value range for future sustainable supply capacities. A range was estimated as the data were deemed too uncertain at this time to give a single reference value. Furthermore, the data were not judged as robust enough to follow a probability approach (such as calculating a standard deviation). Such an approach would add scientific credibility to results and should be pursued as a future research need, in combination with efforts to improve data reliability (see also the Discussion). For these reasons the sustainable supply range developed by this article reflects the first steps towards developing a more robust sustainable supply range and should be regarded as indicative. To this end, the selected range reflects round, easy-to-communicate numbers based on the results, using best judgment and a pragmatic approach to estimation.

At the global level a range of +/−15% from the realistic potential estimate was applied to 2020 and +/−20% from the realistic potential estimate was applied to 2050. This was done to reflect the growing uncertainty over time as knowledge regarding impacts such as climate change, weather, productivity, expansion of infrastructure, etc. becomes less robust over longer periods of analysis. In 2020 this range reflects the full range of the sensitivity analysis, in particular the key parameters regarding harvesting 70% to 90% of NAI (+/−13%). In 2050 it takes into account the full range of the sensitivity analysis (with the exception of an increase of +35% based on a widespread increase in the share of FAWS), as well as the available estimates in the literature (e.g., −20% by [34]).

At the EU level a range of +/−7.5% from the realistic potential estimate is applied to 2020 and +/−10% to 2050. The narrower range reflects the lower range of uncertainty within the EU compared to the global level. With regard to the results of the sensitivity analysis, it is somewhat smaller than the range estimated for 2050 for, e.g., productivity changes in natural forests (+16 to −14%), but was adjusted to better correspond with the literature.

2.3. Use of Per Capita Values for Benchmarking Consumption Levels

The use of per capita values provides a transparent and simple method for meaningful comparisons of consumption levels, with the advantage of clear communication as well as reducing the risk of loopholes and corruption. It is also rooted in a long history of application. In particular, the concept of "environmental space" [35,36] and "ecological footprint" [37] rely on per capita comparisons. Per capita values may also be used to indicate "fair shares", which implies an equal per capita distribution of global resource use and has become a practical and morally widely accepted rule of attribution of either pressures or available resources [27]. This article begins the discussion of whether the principle of global fair shares is an appropriate basis for benchmarking timber consumption levels.

Per capita calculations were made by dividing the derived potential sustainable supply ranges by world and EU population statistics in 2010, based on UN and Eurostat population statistics, and projections until 2050, based on UN population statistics.

3. Results

3.1. A Reference Value Range for Current Levels of Supply

The amount of timber that can be globally extracted under "current" conditions of sustainable forest management ranges between 2090 Mm^3 (using 80% of the NAI in the low potential) and 12,330 Mm^3 (using 100% of the NAI in the high potential). The realistic potential ranges from 3740 Mm^3 (80% of NAI) to 4607 Mm^3 (100% of NAI). Table 3 presents global results for each of the potential ranges. The upper "low potential" and lower "realistic potential" estimates are around the same order of magnitude as [17], which estimated that total annual growth was 3200 Mm^3 on the forest available for wood supply, of which they judged 2700 Mm^3 as potentially commercial, as well as [34], who estimated an economic potential of 3700 Mm^3 on global FAWS.

Table 3. Range of "current" sustainable supply capacities (Mm^3).

Share of NAI	Low	Realistic	High
		Global	
100%	2610	4670	12,330
90%	2350	4210	11,100
80%	2090	3740	9860
		EU	
100%	507	790	887
90%	457	711	798
80%	406	632	709

Table 3 also depicts the absolute sustainable supply capacity of the potential ranges for the EU-27 (406–887 Mm^3). The realistic potential estimates seem to roughly reflect the results of the literature review for the EU-27 (see below).

The per capita global sustainable timber supply (in other words, the reference value) ranges between 0.30 m^3/cap (using 80% of the NAI in the low potential) to 1.79 m^3/cap (using 100% of the NAI in the high potential) with 0.61 m^3/cap as the realistic potential estimate in 2010. In comparison to world production [16], estimated world production at 0.48 m^3/cap in 2005, whereas [38] estimated world production at 0.62 m^3/cap in 2005. This implies that global production levels, which are equivalent to primary consumption levels at a global scale, are either close to or around the realistic potential reference value for sustainable supply.

The EU sustainable supply reference value ranges from 0.81 m^3/cap (80% of NAI in the low potential) to 1.77 m^3/cap (100% of NAI in the high potential), with the realistic potential around 1.34 m^3/cap in 2010. Consumption of primary timber in the EU-27 is estimated by [3] to be around 1 m^3/cap, indicating that estimated EU consumption levels are currently below the EU reference value, but significantly higher than the global reference value in realistic potential estimates.

The sustainable supply reference value range for the EU-27 is thus significantly higher than the global sustainable supply reference value range for the low and realistic potentials (Figure 1). Specifically, more than twice as much timber is available on average in the EU than globally in the realistic potential estimates. Indeed, the share the EU contributes to global sustainable supply capacity is 19% in the low potential estimate, 17% in the realistic potential estimate, and 7% in the high potential estimate.

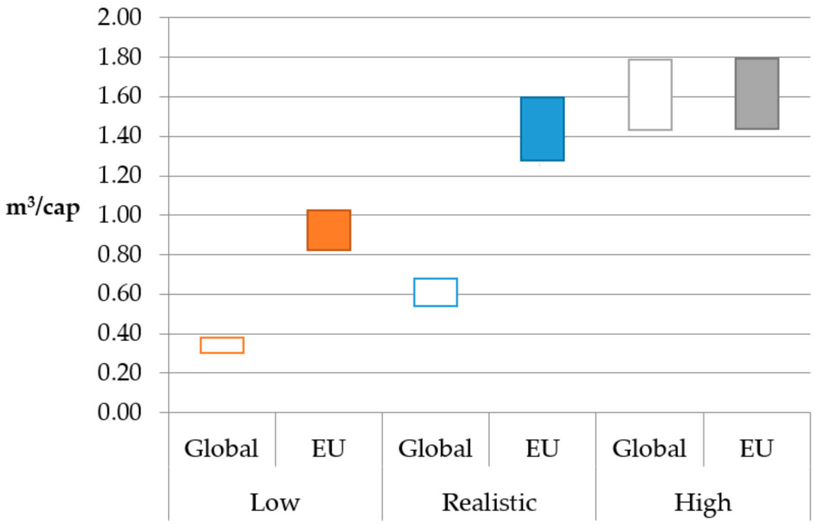

Figure 1. Reference value range for global sustainable supply and EU sustainable supply, m^3/cap, 2010. Note: The range depicted reflects the share of NAI in each of the potentials (80–100%). Population statistics are based on the year 2010 whereas forest statistics are derived from most recent available year at the time of analysis (in 2014).

3.2. Toward a Reference Value Range for Future Timber Supply

3.2.1. Results of the Scenarios Halting Land Use Change

The global SOS scenario for land use change showed a total forest area loss of −1% to −4% and an increase in plantation area of +12% between 2010 and 2050. The global timber supply volume was shown to increase by +1% in 2050, with a −2% supply loss from natural forests and a +15% supply increase from fast-growing timber plantations compared to 2010. In the EU, the total forest area available for wood supply was shown to increase by +4% (with a +15% increase in area of fast growing plantations) and the total supply was shown to increase by +3% in the SOS scenario.

3.2.2. Results of the Literature Review

The literature review showed that at the global level, studies appear to focus more on business-as-usual changes in forest area trends [39–41]. None of the studies assessed considered sustainability constraints to land system change related to the concept of safe operating space. Moreover, while a large number of studies have been published on the potentials to increase the supply of bioenergy [42], these largely focus on either plantations or residues and lack a systemic perspective of total land use or total supply. The authors of [34] assessed both business-as-usual and sustainability trends by extrapolating deforestation trends between 1990 and 2000 to estimate the available forest area in 2050. They then assessed five scenarios for global timber volume ranging from a theoretical potential (excluding protected areas) to an ecological-economic potential (including limitations related to FAWS and harvesting only on disturbed forests). They developed a wide range of results, spanning 1800–8500 Mm^3 of timber available in 2050.

A more robust selection of studies assessing sustainability were available at the EU level. These are summarized in Table 4. All in all the studies reviewed seem to judge the sustainable supply capacity from EU forests between around 620 Mm^3 and 700 Mm^3 per annum over the 2010 to 2050 period, with little variation over the years. In indicative calculations, stemwood is estimated to supply around 92% of the low range and 87% of the high range estimate, due to an increasing supply of residues (comprising 10–12% of the total supply) and stumps (1.5% of the supply) judged to be available in the high range estimates with some consideration of sustainability. This depicts that the literature for the EU presents a more narrow range for sustainable supply capacity than the global picture, due most likely to the better data available at an EU level. It also shows that the state of research regarding sustainable supply capacity at the EU level is more advanced than the global level, with a higher level of differentiation for different sources of supply taking into account both ecological and, in a more limited way, socio-economic constraints in a more robust way.

Table 4. Literature review of the literature assessing EU sustainable timber supply capacities.

Geographic Scope Year Source	Methods	Results
• Europe (results recalculated for EU-27 minus Malta and Romania) • 2020/2030 • [2]	FAWS area increases at same rate as 2005–2010, net increment increases by 11% due to climate effects. Sustainable supply capacity based on EFISCEN model. Four scenarios modeled (reference, maximizing carbon, promoting biodiversity, and meeting energy targets)	129 Mha FAWS in 2020 with an increment of 770 Mm^3/a and a sustainable supply of 568 Mm^3 (over bark) o.b. of stemwood. The study estimates an additional potential of harvest residues, stump extraction and landscape care wood of 135 Mm^3 depending on the scenario
• EU-27 excluding Cyprus, Greece and Malta • 2030 • [43]	Modeled realizable potential supply for stemwood, branches and residues, stumps and other biomass using the EFISCEN model for 3 scenarios ranging from low to high mobilization of wood. Low scenario implies stricter environmental regulations (e.g., no fertilization to compensate residue and stump extraction) whereas the high mobilization scenario allows such intensive management approaches with likely consequences for biodiversity	In 2030 the scenarios result in a realizable supply of:
		623 Mm^3 o.b. (with around 580 Mm^3 from stemwood, 30 Mm^3 from residues and 10 from thinnings)
		731 Mm^3 o.b. (with around 600 Mm^3 of stemwood, 100 Mm^3 logging residues)
		895 Mm^3 o.b. (with a little more than 600 Mm^3 stemwood, 150 Mm^3 residues, 100 Mm^3 stumps and 40 Mm^3 from thinnings)
• Europe (30 countries individually, excluding Russia) • 2050 • [44]	The European Forest Information Scenario Model was used to make projections for 4 scenarios starting from a base year of 1990: (a) BAU, (b) EFISCEN European timber trend studies, (c) maximum sustainable production; and (d) multifunctional management (stable after 2020)	647 Mm^3 o.b./a. in the maximum sustainable production scenario with an average NAI of around 5 m^3 ha^{-1} a^{-1} throughout the simulation period (irrespective of the scenario)
• E8 27 + Turkey • 2020 • [45]	Estimate theoretical potential of raw wood (annual growth on commercially exploited wooded areas) using forecast estimates from EFSOS I	Theoretical potential of 341 million bone dry tonne (bdt) (682 Mm^3) with a technical potential for energy of 66 bdt (133 Mm^3) with 30 million bdt (60 Mm^3) coming from logging residues
• EU 27 • Current potential • [46]	Assessed the additional bio-technical (how much more wood could be physically removed on a sustainable level) and socio-economic potential (how much wood could be cut and brought to market; this is estimated at 35% of the additional bio-technical potential based on expert estimates)	Stemwood: 231 Mm^3 bio-technical potential/81 Mm^3 socio-economic potential
		Harvest residues from current fellings: 149 Mm^3/52 Mm^3
		Harvest residues from additional fellings: 29 Mm^3/10 Mm^3
		Stumps: 176 Mm^3/0 Mm^3 (due to sustainability concerns)

3.2.3. Results of the Derivation of a Future Sustainable Supply Range

At the global level the sustainable supply range is estimated to span between around 3200 Mm^3 and nearly 4400 Mm^3 in absolute terms in 2020. The range expands in 2050 to between around 3100 Mm^3 and around 4600 Mm^3 in 2050 (Figure 2).

At the EU level the sustainable supply range spans between around 600 Mm^3 and 700 Mm^3 in 2020 and between around 590 Mm^3 and 720 Mm^3 in 2050 (Figure 3). The lower range reflects scenarios toward higher levels of forest conservation in the EU.

In both cases, the sustainable supply range reflects the estimated maximum zone of sustainable supply capacity. Using the forest for timber supply at a rate under the sustainable supply range would be within the SOS for timber production. This is indicated in Figures 2 and 3 with a dark green shading of the potential volume below the calculated sustainable supply range and a light green shading reflecting the maximum range of sustainable supply capacities. As the EU reflects a territorial perspective, this article terms the EU space as a safe operating space for EU timber production.

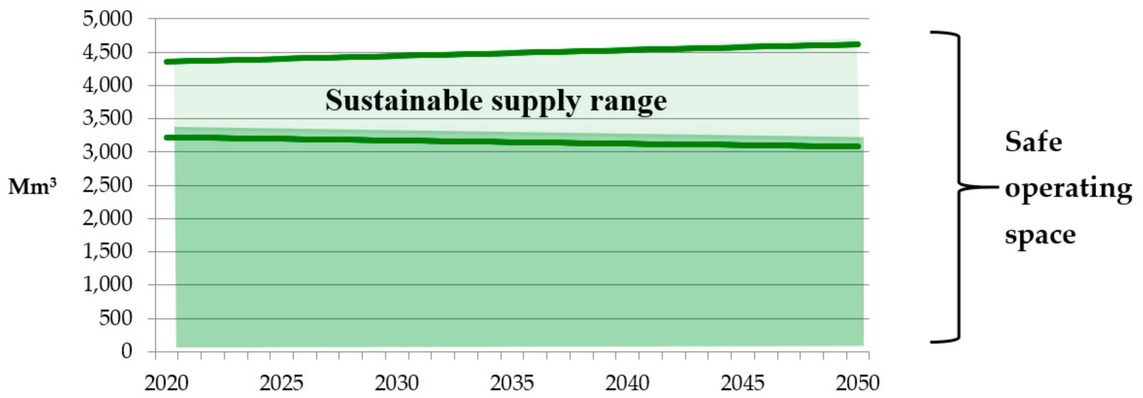

Figure 2. Global sustainable supply range under the safe operating space scenario, 2020–2050.

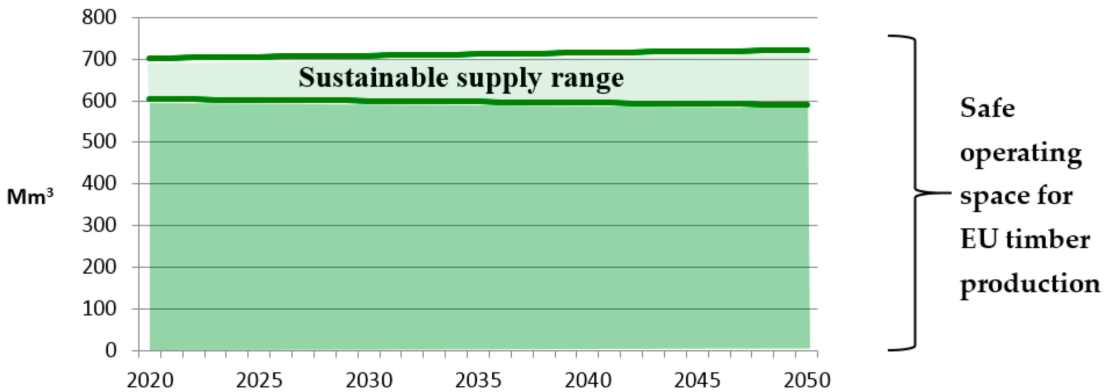

Figure 3. EU sustainable supply range under the safe operating space scenario, 2020–2050.

3.3. Toward Per Capita Reference Values for Benchmarking Consumption Levels

With regards to an initial benchmark for consumption levels, Figure 4 depicts the per capita reference value range based on global sustainable supply capacities. It varies between around 0.42 and 0.57 m^3/cap in 2020 and between around 0.32 and 0.48 m^3/cap in 2050. The median estimate is nearly 0.5 m^3/cap in 2020 and around 0.4 m^3/cap in 2050. The decrease over time is due to increasing population. Indeed, while the sustainable supply range in absolute values shows an increased availability over time (due to the increasing productivity of plantations as well as the increased uncertainty space broadening over time), population growth implies that less timber will be available on a per capita basis in the future.

Figure 5 depicts the per capita reference value range for the sustainable supply capacities of EU forests. It varies between around 1.2 and 1.4 m^3/cap in 2020 and between around 1.1 and 1.4 m^3/cap in 2050. The median estimate decreases slightly across the time period to reach around 1.25 m^3/cap in 2050. This indicates that the effect of population in terms of timber availability is not as high as observed at the global scale. This is because the EU expects a higher degree of stabilization of the population, so that per capita trends more closely mimic total trends. The EU sustainable reference range in per capita terms is presented for comparative purposes (assessing sustainable production of EU forests does not require a population parameter). This implies that consumption levels within or below the EU reference value range are not "per se" sustainable, especially if they exceed the global average. This raises the question of which reference value is appropriate for the EU (see Section 4.2 in the Discussion).

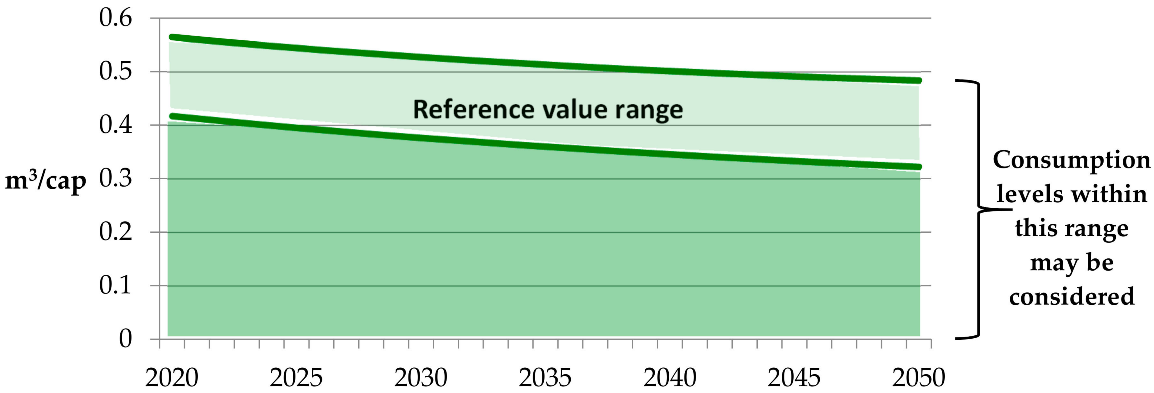

Figure 4. Global reference value range for benchmarking sustainable consumption levels based on per capita derivations of global sustainable supply capacities, 2020–2050.

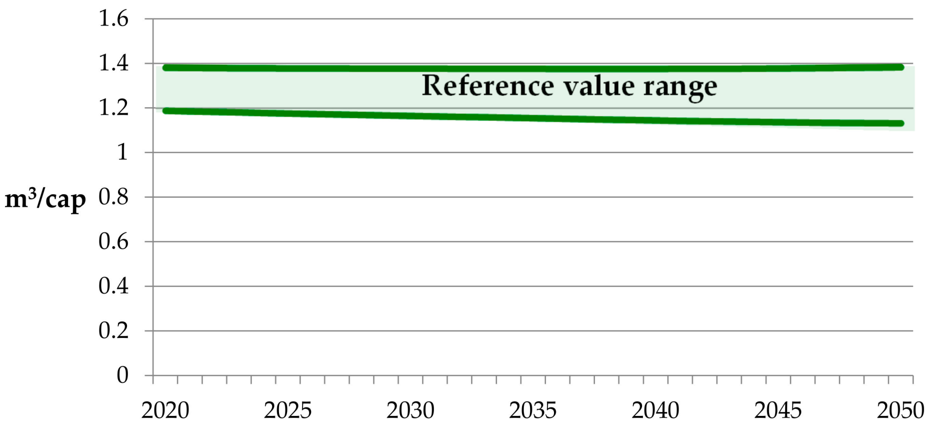

Figure 5. EU reference value range for benchmarking consumption levels based on per capita derivations of EU sustainable supply capacities, 2020–2050.

4. Discussion

The reference value ranges for sustainable supply capacity presented in this article depict a wide range of estimates. This reflects challenges related in particular to data availability and methodological robustness. It means that the results should be interpreted with caution and seen as a first step toward developing a method to, e.g., incorporate safe operating space concerns regarding land use into estimations of future sustainable timber supply capacities, and to, e.g., consider how such supply constraints may be translated into reference values (and eventually toward targets) for benchmarking sustainable levels of consumption. Section 4.1 discusses some of the key challenges for strengthening the reliability and applicability of results. Section 4.2 discusses the results in more detail and considers implications with regard to appropriateness for the EU policy context. Finally, key future research needs are highlighted (Section 4.3).

4.1. Challenges Relating to the Methodological Approach and Data

The basic approach to aggregate national data on sustainable supply seems appropriate for estimating sustainable supply capacity, in particular due to major differences in forest types and management across the world. However, better and more harmonized national data is needed for this approach to produce more reliable results.

With regards to forest measurement, better Earth observation data combined with harmonized surveys would greatly enhance knowledge on forest area and forest growth. This article relied primarily on source (e.g., FAO, International Tropical Timber Organization (ITTO), etc.) reporting data based on surveys of countries. In some cases this means that estimates given by countries on, for instance, their forest area, have been generated using different methods and with different levels of reliability. Some countries also opt out of reporting or may significantly change their reported data between years. With regards to data sources specifically dedicated to fast-growing plantations, this article heavily relied on the FAO Planted Forests Database, which is subject to similar problems (consistency, reliability, and lack of harmonization due to the survey method of data generation). Along with other sources on fast-growing plantations, the data is also somewhat outdated. Outdated data, or data from different years, has been a challenge for all types of forests. Efforts were taken to use the most recent and reliable sources for both area and productivity at the time of analysis, but as this was not always possible, older data was sometimes relied on. This also means that data may not always be 100% comparable. Advanced remote sensing processes would dramatically improve data quality, not only for forests as a whole, but also for plantations. This is critical to generating reliable scientific evidence on limits. Progress to this end is being made. For example, [47] was the first study to use Landsat Earth observation data to map global forest loss.

A key challenge is estimating how sustainable forest management could be reflected in the sustainable supply capacity estimates of global forest use. By its definition, the concept of sustainable forest management generally includes maintaining multiple functions of forest systems across social, economic, and environmental dimensions. However, to estimate sustainable supply, an indication of timber removal only (i.e., harvesting below NAI as a maximum threshold) is relied on. How other functions of the forest can be better taken into account is an open question for future research. In particular, research should consider the issue of scale, asking what scale is appropriate for estimating a balance between the rate of timber removals and, e.g., maintaining other ecosystem services. The indicator "share of NAI" has the benefit of being a transparent and relatively simple indicator that can be applied at multiple scales of analysis. However, as an indication of sustainable harvest rates, it also depends on the structure and age of the forests, as well as the period assessed. This is because even-aged stands reach a point of no or even negative growth, implying that in countries with a high share of old forests, harvest rates could be above NAI for a short period of time. On the other hand, countries with a high share of young forests may keep harvests well under NAI to allow the forest resource time to grow. This means that the "share of NAI" may be most appropriate to countries, regions, or forests with an even distribution of trees in each age class. Related economic and environmental dimensions should also be further explored in future research—e.g., considering price shocks associated with periods of intense harvesting as well as the ecosystem functions associated with older stands in particular. Additionally, future research may explore alternatives, such as ways to incorporate the structure and quality of standing stock, looking at actual harvests, or aggregating local data on sustainable forest management to national and global levels. Approaches to incorporate residues as well as thinnings more comprehensively, in light of environmental constraints related to, e.g., soil fertility, and also timber demands related to, e.g., energy, should be assessed. Altogether this implies that a future indicator of sustainable supply may become more comprehensive and dynamic, considering harvest rates under criteria of sustainable forest management as well as timber availability (stocks and usable growth). If NAI is judged as the most reliable and feasible metric for estimating sustainable supply capacities, research is needed to consider how much of NAI can and should be removed globally under different conditions of sustainability (considering multi-functional forest uses) for different types of forests (e.g., plantations, semi-natural, managed, etc.) and in different regions of the world.

With regards to future trends, changes in the root causes of deforestation (including population, economic growth, and national and international demand for agricultural products, wood products, and minerals [48]) make it difficult to extrapolate past trends as indicative of future developments. Forest productivity and management assumptions are also prone to uncertainty, especially over the long term. With regards to productivity, climate change could dramatically change forest structure and growth, as well as increase the risk of disturbances such as fire and pests. It is difficult to foresee such impacts and better modeling of potential impacts on the global level especially is needed to provide a more realistic picture of potential future supply capacities. At the same time, forests are also crucial to efforts to mitigate climate change. Strategies to raise carbon storage by adjusting management practices in forests would certainly have an impact on sustainable supply capacities [2].

Strengthened data is needed regarding historical developments, the current situation, and potential future developments. For example, there is a lack of data on the historical development of the area of forest available for wood supply. While this is dependent on regional elements like terrain, infrastructure development, zoning, and conservation, which may be difficult to aggregate to a global level or transfer to other countries, the large differences in forest available for wood supply (e.g., around 50% globally compared to 85% in the EU) suggest that some indications of historical developments may be useful to set the context for potential future developments.

With regards to the SOS scenario, the method to define the boundaries of such a scenario should be strengthened, in particular through multi-stakeholder discussions on the amount of forest area change that could be considered within an acceptable degree of risk, taking into account the precautionary principle. To this end, existing targets could help set the context, such as the Aichi Biodiversity Targets with the aim to at least halve the rate of loss of all natural habitats, including forests, by 2020 [29]. To enable such a stakeholder process for delineating the safe operating space, more robust knowledge on the dynamic processes of land use change for forestry and its relation to other planetary boundaries would be beneficial. In particular, the potential for afforestation on degraded land and the relationship between forestry and agriculture land use change should be explored.

Finally, with regards to the derivation of reference values to translate the safe operating space into benchmarks for consumption, challenges relate in particular to population growth. Uncertainty regarding assumptions about population growth make long-term per capita reference values subject to higher uncertainty. Especially long-term variation in population prognoses may have a significant impact on long-term reference values. This may make a range more appropriate, but would also make benchmarks less suitable for possibly developing into targets that are easy to communicate. The political implications of data uncertainty and related challenges for developing per capita benchmarks, and eventually targets, should be addressed by future research.

4.2. Challenges for Interpretation: Is a Global or EU Reference Value Appropriate for EU Policy Orientation?

This article has presented both global and EU current and future reference values for benchmarking consumption. It has been shown that the EU-27 is estimated to have a per capita sustainable supply potential that is around 2.3 times higher than the global average in 2010 (realistic potential estimates), between 2.6 and 3.1 times higher than the global average in 2030 and between 2.9 and 3.5 times higher than the global average in 2050. The question of which reference value the EU should orientate towards, or if alternatives are needed, is an ethical discussion that should take social, legal, ethical, and political considerations into account.

On the one hand, countries with a large forest resource seem to have built up a larger cultural significance to both the forest and forest products. In terms of renewable energy, it seems reasonable for countries rich in forests to use a higher share of timber on a per capita basis (e.g., in local supply and demand chains) than countries with no local resources (e.g., Qatar and Egypt, which seem to have a greater opportunity to use, e.g., solar power, also considering that the heating demand is not as high compared to some forest-rich countries such as Sweden and Finland). This would imply that timber is not a global resource to which every global citizen has the same right. On the other hand, global forests are a common concern of humanity. They are a carbon sink and strongholds of biodiversity. Overuse of the global timber resource surpasses a planetary boundary with universal consequences. Moreover, the concept of a 'safe and just operating space' [49] suggests that limited natural resources critical to meeting basic human needs (including shelter and energy) must be shared in a humane way. In other words, a highly disproportional distribution of use is not sustainable, if it means that a portion of the global population consumes at levels under the minimal conditions for a dignified life. Both environmental and social concerns imply that a global reference value is appropriate, with equal distribution being the most transparent and fair method.

Taken together, these perspectives highlight that the challenge for reference values in relation to forestry seems to be more nuanced than comparable efforts toward global targets or reference values, such as for cropland. For example, one could argue that cropland for food production relates to more of a basic human need than forests; in other words, the right to food and freedom from hunger. This is a discussion on the concept of "fair shares" for different types of resources that must take place at an international level in a multi-stakeholder context. At its core, the challenge for forestry is how to take regional variability into account when considering global capacities. All in all, it is about smarter consumption (balanced with regional and global capacities) with the aim of preventing problem shifting. Keeping the climate challenge in mind and the need to reduce fossil fuel use in a smart way, the question is about finding a middle space between two extremes: (1) problem shifting induced by too high of demand and (2) a protectionist type of market with no trade.

Both global and EU reference values could be valuable as an orientation for European policy makers. In particular, a reference value on global sustainable supply can be used to prevent problem shifting—for instance striving to meet other global targets (like climate targets) in a way that crosses other planetary boundaries (like land-system change). Alternative approaches to develop reference values could be explored by future research. One option could be to distinguish among "levels of sustainability" within a reference value range. Another option could be to develop adjusted reference values, for example developing a reference value for the "sustainable supply capacity for the rest of the world" (subtracting the EU's share from the global sustainable supply capacity) and applying this to net imports. Such alternatives should be tested against social and environmental sustainability criteria, in particular considering global equity and global risks of deforestation, and should be cautiously explored in an interdisciplinary and multi-stakeholder context. Finally, the rather broad reference value range developed by this article, in particular with the perspective to 2050, could be adjusted over time and as better research becomes available.

4.3. Future Research Needs

Altogether key areas for future research may be summarized as follows:

- Strengthen sound science on indicators for sustainable forest management, in particular considering the harvest rate under sustainable conditions and for different types of forests
- Develop supply scenarios to better understand the structural change happening between fast-growing plantations and natural forests domestically and abroad, as well as the potentials for residues under sustainability considerations
- Consider how afforestation on degraded land could play a role in the safe operating space and derived reference values
- Deepen knowledge on the systemic interaction of the safe operating space for forestry land use change with other planetary boundaries
- Consider how population variation can be accounted for in long-term reference values or targets, taking into account the role and aims of reference values and targets in the overarching context of transition management

- Develop socially and scientifically acceptable ways to integrate the precautionary approach and deal with uncertainty regarding the rationale behind the global safe operating space concept
- Deepen the analytical framework for understanding the advantages and disadvantages of EU versus global sustainable supply reference values in light of the principles of sustainable development, as well as the potential impacts on national competitiveness.

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